# Field Evaluation of Descent Advisor Trajectory Prediction Accuracy for En-route Clearance Advisories

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## Abstract

The Descent Advisor (DA), a decision support tool for en-route air traffic controllers, underwent a series of field evaluations from 1992-95. DA assists controllers by advising fuel-efficient conflict-free clearances that conform to traffic-management-flow-rate constraints. The most recent test evaluated DA trajectory-prediction accuracy, and procedures, for precise and efficient descent management. An air-ground data link was also used to investigate the exchange of data (winds, speed, and weight) for improving trajectory predictions. Trajectory-prediction accuracy was evaluated for several types of clearance advisories including cruise speed, cruise altitude, pathstretch (delay) vectors, and descent-speed profile with top-of-descent. The descent-speed advisories were evaluated for both on-route and off-route navigation. Results for the on-route descents were published previously. The purpose of this paper is to present the trajectory-prediction accuracy results for the remaining advisory cases. Results are compared between aircraft types that differ in terms of performance (jets and turboprops) and navigational capability (with and without flight management systems). In addition, the on-route descent cases are revisited to account for errors associated with radar-track anomalies and weight estimation. The results, which support performance metrics for en-route conflict prediction/resolution and arrival management, may be used to improve ATM tools to enable more efficient flight operations.

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## Introduction

The civil-air-transportation community has adopted the concept of Free Flight as a goal for increasing user (aircraft operator) flexibility and flight efficiency (time and fuel) in the future Air Traffic Management (ATM) System. The RTCA Task Force 3, in its final report on Free Flight Implementation, has identified that the primary role of controllers in the future ATM system will be to perform "separation monitoring and prediction functions."[1] Future ATM decision support systems will require "much more functionality than today, enabling the controller to perform a wider range of tasks including a greatly enhanced role in traffic management."

To deliver Free-Flight benefits in high-density airspace, ATM decision support tools (tools) must be developed to detect /resolve problems (such as potential conflicts) and enable greater efficiency for the users. Efficiency may be improved by allowing users to plan, and fly, preferred trajectories with minimal deviations (due to procedures or corrective clearances).[2,3] The "zig-zagging" that users observe today, as they fly across sectors, may be reduced by conflict-free planning with consideration for flow-rate constraints (metering or miles in trail (MIT)). New methods are needed to improve the accuracy of conflict prediction as well as the efficiency of solutions for conflict resolution and flow-rate conformance. Supporting ATM tools will depend heavily on the accuracy of their trajectory predictions.

The development of accurate trajectory-prediction capability has been a fundamental goal of Center-TRACON Automation System (CTAS) technology development. CTAS is a set of ATM tools designed to assist controllers in maximizing the efficiency of the extended terminal area (including the en-route transitions into, and out of, the terminal airspace).[4,5,6,7] The en-route element of CTAS is the Descent Advisor (DA). The DA tool is designed to help controllers develop accurate conflict-free trajectory plans which conform to flow-rate constraints in a user-efficient manner. Another CTAS tool, referred to as the Conflict

Probe and Trial Planner (CPTP), was "spun off" from DA in 1996 and used to evaluate stand-alone (without flow conformance) conflict-probe technology.[8] A quantitative study of conflict probe performance has also been conducted. [9]

Several other en-route ATM tool concepts, of a similar nature to CTAS, are under development in both the U.S. and Europe.[10,11,12,13,14,15,16,17] Although there have been efforts to evaluate these concepts, there are few results published in the literature regarding actual trajectory-prediction-accuracy performance, particularly field-test results.

Following extensive pilot- and controller-in-the-loop simulation in the mid-to-late 1980's, the DA tool underwent a series of field evaluations from 1992-95. These tests evaluated DA trajectory-prediction accuracy as well as procedures for efficient descent management. The first two tests used a highly instrumented flight-test aircraft to measure the sources of trajectory-prediction errors and investigate techniques for integrating flight management systems (FMS) and DA.[18,19,20] An arrival-time accuracy on the order of 20 seconds was measured for typical descent predictions with time horizons of approximately 15 minutes. The results indicated that wind-prediction errors were the largest contributing error source. Along-track wind errors for both tests were measured to be 10-15 knots in cruise and 5-10 knots in descent, with standard deviations of approximately 10 knots in all phases of flight. The test also evaluated several flight-deck concepts for reducing errors including lateral navigation, precise speed profile tracking (e.g., elevator on speed), and several vertical-profile-navigation techniques ranging from simple range-to-altitude feedback to performance-based vertical navigation. These flight tests facilitated early experimentation and validation of DA and paved the way for field testing with regular traffic.

The most recent test, conducted in 1995, involved commercial flights with a wide variety of performance types (jet and turboprop) and navigation capability (conventional and FMS equipped). [21,22,23,24] Trajectory-prediction accuracy was evaluated for en-route clearance advisories including cruise speed, cruise altitude, pathstretch (delay) vectors, and descent-speed profile with top-of-descent (TOD). An air-ground data link was also used to investigate the exchange of data (winds, speed, and weight) for improving trajectory predictions.

The descent-speed cases were divided into two categories of arrival routing, on-route and off-route. The on-route category included all FMS-jet cases, and conventional-equipped aircraft (jets and turboprops) that navigated along Standard Terminal Arrival Routes (STARs). FMS jets were considered "on route" even when cleared direct to a fix. The off-route category included conventional-equipped aircraft (jets and turboprops) on "direct" clearances (e.g., vectors) to the meter fix. Results for the on-route descent-speed cases are presented in reference 24.

The purpose of this paper is to present the trajectory-prediction accuracy results for the remaining advisory cases. Results are compared between aircraft types that differ in terms of performance (jets and turboprops) and navigational capability (with and without flight management systems). In addition, the on-route descent cases are revisited to account for errors associated with radar-track anomalies and weight-estimation.

Many of these results are applicable to metrics for the accuracy of en-route conflict prediction as well as the fuel/time efficiency of advisories for conflict-resolution and descent-management. Knowledge of real-world trajectory-prediction errors will improve the ATM system in two ways. First, the knowledge may be used to improve the performance of ATM tools and provide a greater level of accuracy for clearance advisories. Second, the data may potentially justify reductions in separation buffers that are necessitated trajectory uncertainty. For example, detailed trajectory-prediction-accuracy results can be used to determine minimum conflict-probe separation buffers as a function of aircraft type, phase of flight, and atmosphere. This approach would essentially customize ("shrink wrap") buffers to the capability/performance of each aircraft, and provide users with a business case for equipment upgrades.

The paper begins with a description of the test followed by detailed results and conclusions.

## Test Description

### Approach

The test was conducted at the Denver Air Route Traffic Control Center (Center) over two periods including September 13-29 and October 1 through November 8, 1995. The test focused on Denver arrivals within one of the five Denver Center areas (the northwest). The arrival limitation was due to the FAA Host computer which could only provide arrival data to CTAS at that time). Traffic periods were selected for moderate arrival-traffic conditions and typically occurred in the late morning and early afternoon. Three airlines participated in the test including United Airlines (UAL), Mesa Airlines (Air Shuttle (ASH)), and Mark Air (MRK). A description of the test airspace (sectors and routes) and training may be found in reference 24.

A field-test version of CTAS, including both the DA and Traffic Management Advisor (TMA) tools, was temporarily installed at the Denver Center and activated during discrete test periods. For this test, TMA was operated by a CTAS engineer to provide DA with conflict-free meter-fix scheduled-times of arrival (STAs) based on actual traffic demand and airport capacity.[25] A cadre of three full-performance-level controllers (test controllers) interacted with the DA tool and coordinated clearances with the controllers working at the appropriate sectors. Although DA was originally designed to integrate the advisories directly onto the controller's radar display, this approach allowed for the evaluation of DA-advised clearances without a full system implementation and training at all sectors.

A test engineer monitored the use of DA advisories to facilitate the collection of trajectory-prediction data. Trajectory predictions and radar data were recorded for later comparison to determine prediction accuracy. To be as conservative as possible, DA-advised clearances were issued without corrective updates to lengthen the time duration of each trajectory prediction to allow maximum error growth. For the off-route descent cases, however, controllers were allowed to vector flights per normal operational procedures (without help from DA).

Test System

The system set-up is illustrated in figures 1 and 2. The CTAS system included a DA station, located next to the test sectors, and a TMA station, located adjacent to the TMU (approximately 75 feet from the participating-sector positions). The DA station included an alphanumeric auxiliary-display/interface, for the test controllers, and a full DA color-graphical-user interface for the test engineer. The alphanumeric interface was designed to investigate a simple meter-list display concept that would be possible to implement on the current Plan View Display (PVD) hardware. A detailed description of the DA interface used for this test may be found in reference 24. The full DA interface was used for data collection and conflict prediction/resolution (to set up conflict-free test conditions).

CTAS received real-time updates of radar-track and flight-plan data for arrivals from the Center's Host computer via a one-way (Host-to-CTAS) interface. CTAS also received predictions of the winds and temperatures aloft based on the Rapid Update Cycle (RUC) 3-hour forecast.[26,27] The TMA station also included a data-link communications terminal which was used to access part of the UAL dispatch database, and facilitate two-way data-link communications with about half of the participating UAL flight crews. The data exchange included the downlink of aircraft weight, for input to CTAS, as well as aircraft and atmospheric state (Mach/airspeed, temperature, and wind) for cross-checking Host track and RUC atmospheric data. In several cases, winds from the CTAS descent profile were uplinked to FMS-equipped aircraft for use in the airborne descent calculations Unfortunately, it was not possible to analyze the wind-uplink cases because the original FMS wind-data was not available for comparison. However, the weight data was used to determine the impact of actual weight-estimation errors on the trajectory predictions.

Figure 1. DA test setup (DA station).

Figure 2. DA test setup (TMA station).

DA Tool

This sub-section describes the DA tool in terms of the Trajectory Generation process, the DA Advisory Generation process, and the typical Delay Maneuvers for which the advisories would be used.

Trajectory Generation

DA trajectories are generated by integrating a set of point-mass-model equations of motion in a manner similar to a “performance-based” FMS. The trajectory modeling includes corrections for non-standard atmospheres and factors for wind-gradient (velocity change with altitude). For a typical jet, descent rates (and top of descent) will vary by approximately 3% for each 1 knot/1000 ft of gradient.[18] Turn dynamics are based on speed and airspace/altitude regime (including “fly-by” and “fly-over” waypoint turns). Ascent/descent profiles are computed using detailed performance models to reflect the influence of aircraft weight, speed profile, and atmosphere, on acceleration and ascent/descent rate.[28] Speed profiles are modeled to vary with phase of flight (ascent, cruise, and descent) and include appropriate Mach/ indicated airspeed (IAS) transitions. Several studies have demonstrated good agreement between CTAS and several FMS systems (for en-route descents to a crossing restriction) with differences primarily related to input data (thrust/drag/weight data, winds, and tracking).[18,23]

The fidelity of a detailed performance-model approach offers three advantages. First, the accuracy may be tuned through data. Second, it enables the ATM tool to customize advisories to the unique characteristics of each aircraft (e.g., speed envelope) without requiring the controller to memorize the details (analogous to an FMS supporting a pilot). Third, the approach facilitates compatibility (agreement) with airborne FMS systems.

One exception was made to the DA altitude-profile-modeling approach for en-route cruise-altitude changes. If the change involved a descent, the descent profile was based on a flight-path angle (an assumption that was felt to be adequate for this situation). The goal of the cruise-altitude testing was to gather data to determine an empirically-based value for the flight-path angle and validate the accuracy of the assumption.

Once DA begins analyzing a particular flight, the trajectory predictions are continuously updated to reflect changes in aircraft state (position, altitude, and velocity) and controller intent. Nominally, the predicted path is based on the flight-plan route. DA monitors each flight to determine if it is tracking the flight-plan route. If not, DA generates a path to re-join the flight-plan route or join another route designated by the controller. To correct the automatic route-prediction heuristics, DA provides the controller with quick keyboard shortcuts for easy updating of the intent model. These inputs differentiate between vectors to intercept a route, vectors to re-join a route at a fix, or vectors to pathstretch/S-turn a flight prior to re-joining a route. The controller may also constrain the trajectory solutions in terms of cruise altitude, cruise- and descent-speed profile (Mach/IAS), and top-of-descent location (TOD). These constraints enable DA to complement individual controller technique and to adapt to pilot-imposed constraints such as speed changes for turbulence penetration, or path changes for weather avoidance.

Vertical profiles are generated to be in conformance with ATC constraints such as altitude and/or speed restrictions at a fix. If a constraint is predicted to be impossible to meet (e.g., an arrival that is too high), DA predicts the deviation from the constraint and reports it to the controller. Within those constraints, the profiles are generated to be fuel-conservative (i.e., minimum flight at lower altitude), and to be as close as possible to the user’s preference (as defined by the pilot or airline operational control). Preferences may be defined in a database or input in real-time. Currently, a database is used to define default descent-speed preferences as a function of aircraft type and user. Descent speed and other preferences (e.g., route, altitude, cruise speed, or an entire 4D trajectory) may be defined by the user for individual flights and provided to DA via manual input, extended flight plan, or data link.[2,29,30]

DA Advisory Generation

DA uses the trajectory-prediction process to generate ATC-clearance advisories that conform with flow-rate constraints. These constraints may be in the form of a TMA-generated meter-fix STA or a miles-in-trail spacing. If a flight must be delayed, advisories are generated by iterating on clearance "degrees-of-freedom" (e.g., speed profile, altitude, and routing) until the predicted trajectory meets the flow-rate constraint. The iteration may be performed by the controller, through trial planning tools (a process referred to as “what-if” or provisional planning in previous publications), or automatically by the software. Predicted conflicts (loss of legal separation with other flights) are also displayed to the controller. The conflict display information indicates the flights involved, as well as the time, position, and geometry of the conflict. The controller may then use the DA functions to resolve conflicts (manually or with automation assistance) while maintaining conformance with flow-rate constraints.[31]

Trajectory solutions are translated into ATC-clearance advisories which include cruise speed, cruise altitude, pathstretch (delay) vectors, and descent-speed profile with TOD. Although DA does not currently suggest an ascent speed, the controller can modify the planned-speed profile to correct predictions of the 4D trajectory (including top of climb). The vector advisories include direct headings and pathstretch "delay vectors." Direct headings provide the magnetic heading to the next fix, corrected for wind drift, for aircraft that are not equipped for area navigation. For the pathstretch advisory, DA computes the time/distance to go, along a delay vector, before a turn back will meet the flight's STA. The advisory is displayed in terms of the distance/time to go, and the heading to intercept the desired route at a fix. The pathstretch advisory, which is updated in real time to reflect changes in aircraft position and velocity, may also be used to time the turn back when pilots deviate from the controller's vector instructions (e.g., deviations for severe weather).

In addition to the clearance advisories, DA also monitors flight progress to provide feedback on the flight's conformance to the cleared route, vertical profile (speed and altitude), and flow-rate constraints.

Delay Maneuvers

The challenge to providing "user-friendly" arrival management is to apply fuel-efficient methods to absorb delay while ensuring minimum separation requirements are met. These methods, which span three degrees of freedom (path, speed, and altitude), vary in terms of fuel efficiency and the maximum delay that may be absorbed. Depending on the situation, controllers "value" certain methods differently, with considerations for factors such as workload, complexity, and robustness to surprises (e.g., lost communications). For example, it may be possible to solve a problem with either a vector or change in altitude. Vectors require multiple rounds of communications to initiate and complete. By comparison, a change in altitude requires less attention and only one round of communication. That leaves the controller more time to focus on other situations. ATM tools must attempt to guide controllers to user-efficient solutions, when the options are available, and not conflict with controller preferences during workload-sensitive situations. DA provides the controller with the ability to combine and/or constrain any of the advisory functions to suit their own style.

The purpose of this part is to highlight some of the typical applications of the DA advisories. Although the primary focus of this discussion is time control (the ability to delay or expedite a flight), the maneuvers also apply to conflict resolution. Details on the use of DA conflict-resolution functionality may be found in references 8 and 31. The following discussion is based on a typical arrival scenario involving a jet approaching the terminal area with approximately 150 n.mi. to go.

For small delays, depending on distance to go, speed control is an efficient technique in terms of workload and fuel. Decelerations towards best-endurance speed may not only absorb delay, but also reduce user-operating cost. Speed adjustments may provide a fine level of time control while requiring only one round of communications. Descent-speed selection typically provides 2-4 minutes of control while cruise speed adds an approximately 1-4 minutes (depending on the range/altitude to go, speed envelope, and wind profiles). The combination of speed control and TOD selection allows the ATM tool to provide users with fuel-efficient descents for conventional-equipped aircraft, while minimizing interruptions to airborne-computed profiles flown by FMS-equipped aircraft. Speed may also be used for conflict resolution, however, the relatively small cruise-speed range of most aircraft limit its effectiveness to longer lead-time resolutions as compared with altitude and vector control.

Changes in cruise altitude can be an effective technique for absorbing minor delays (as well as resolving conflicts). A typical descent at constant IAS will reduce TAS (true airspeed) by approximately 4-7 knots per 1000 feet. Depending on the range, altitude profile, speed profile, and winds, jet arrivals can typically absorb 1-2 minutes of delay simply by descending to the floor of the high altitude airspace (typically FL240). Controllers often use this technique to get high-speed arrivals out of strong jet-stream tailwinds. The efficiency of this maneuver depends primarily on speed profile. Fuel efficiency may be relatively insensitive to altitude changes if the aircraft is already slowed to best-endurance speed, otherwise, it may not be fuel efficient. Altitude changes only require one round of communications to implement. If the new altitude is available (free of neighboring flights), this maneuver can be very controller friendly.

For larger delays, beyond speed- and altitude-control ranges, delay vectoring can absorb as much time as airspace permits. Delay vectors involve two controller actions, one to vector a flight off of its routing, and a second to return the flight to its route or STAR. Vectors may also require greater coordination with neighboring sectors. S-turns are a more complicated maneuver that applies multiple turns to add path within a small airspace. DA allows the controller to evaluate ("what-if") both of these maneuvers prior to issuing a clearance. For gross delays (i.e., greater than 8 minutes), holding patterns lend themselves to the efficient use of airspace. Holding patterns, which use altitude for separation, can reduce the workload associated with horizontal separation in high-density airspace. In any case, the pathstretch advisory may be used to hone a delay vector, S-turn, or hold. Although vectors require more controller attention, they can provide the controller with fast action (compared to a change in altitude or speed) for short time-horizon conflict resolutions. Similar to altitude changes, fuel efficiency depends heavily on the aircraft's speed.

DA-advisory degrees-of-freedom are intended to be combined as appropriate (e.g., a pathstretch followed by a descent speed). Normally, cruise advisories will be followed by a descent-speed advisory which can correct any remaining error. As long as the cruise maneuvers get the flight within the descent-speed control envelope, the time errors from cruise can be wiped out by the descent-speed advisory.

Test Conditions

Participating aircraft types were combined into three major categories: FMS-equipped jets (e.g., Boeing 757), conventional-equipped jets (e.g., Boeing 727), and turboprops (e.g., Beechcraft 1900). All participating turboprop types were conventional-equipped (i.e., not equipped with FMS).

Jet types entered the test airspace at cruise altitudes ranging from FL290 to FL410 and at cruise speeds between Mach 0.73-0.85. Turboprop types entered the test airspace between FL210-250 and at speeds between 165-200 knots indicated airspeed (KIAS). On descent, jets were constrained to cross the meter fix (TRACON boundary) at or below 250 KIAS, and at FL190 or 17,000 ft, depending on the STAR. Turboprops were constrained to cross the meter fix at 16,000 ft.

A target set of test cases was identified for evaluating trajectory-prediction accuracy across a representative set of delay situations. Cruise speed advisories were divided into acceleration and deceleration cases, for which an equal number of runs were attempted. Cruise-altitude changes were always for descent (ascents were left for evaluation in future tests), with minimum altitude changes of 4000 ft for jets and 2000 ft for turboprops. Pathstretch advisories were conducted for turn-back angles between 30 and 90 degrees with delay lengths on the order of 1-3 minutes. The DA-descent cases, for both on-route and off route jet cases, were divided evenly between three speed cases: fast (320-340 KIAS), nominal (280-300 KIAS), and slow (250-270 KIAS). For turboprops, the cases included: fast (220KIAS), and slow (160 KIAS).

Weather conditions varied throughout the test and included several periods of thunderstorm activity, occasional pockets of turbulence, and several frontal passages. The winds aloft were generally out of the west and northwest with velocities at the upper flight levels ranging between 40-120 knots.

Results and Discussion

This section presents the results in three sub-sections, each with a focus on a particular profile: Horizontal, Altitude, and Time. Each profile sub-section presents the trajectory-prediction accuracy results for the advisories that impacted that profile. For example, cruise-speed-advisories, which primarily influence time, are analyzed in the Time Profile sub-section only. The off-route descent advisories, however, are analyzed in all three sub-sections because they influence the accuracy of each profile. For cruise-altitude changes, the analysis is limited to the altitude-profile only.

Where applicable, results are presented as a function of aircraft-type to illustrate the variations related to aircraft capability and performance. For brevity, the following naming convention is used: FMS refers to FMS-equipped jets; Conventional aircraft refers to the combination of conventional-equipped jets and turboprops; and Conventional refers to conventional jets only when they are to be compare to turboprops.

It is not expected that the results presented in this paper are statistically significant given the number of runs collected and the large number of factors that influence trajectories in the modern ATM system. However, the data sample does reflect real-world factors that are often lost in simulation, and can provide insight into the actual accuracy of ATM-tool advisories.

Horizontal Profile

This sub-section presents cross-track-accuracy results based on the analysis of the descent-speed cases. The first part re-visits the results for the on-route descents (reference 24) for two reasons: to account for anomalies that were not addressed in the earlier report; and to facilitate comparison with the off-route descent data. The second part presents the results for the off-route descent cases and makes a comparison with the on-route results.

Cross Track Errors – On-route Descents

The analysis in this part is based on the data collected for the on-route descent cases presented in reference 24. Tables 1 and 2 present the cross-track errors as a function of aircraft type. Table 1 lists the mean and standard deviation of the average-cross-track error for each flight. Average cross-track errors were calculated using the absolute value of each flight's mean cross-track to prevent errors of opposite sign from canceling. Table 1 also presents the variation (i.e., standard deviation) of the standard deviation of the cross-track error for each flight. Table 2 presents additional metrics concerning the maximum error across all flights and the mean of each flight's maximum error. Maximum errors were also calculated using absolute values to obtain the largest cross-track error independent of direction. Statistics for the length of flight are provided to indicate the distance horizon of error growth.

Table 1. Cross-track error, on route.

| Aircraft type | Runs | Flight average (mean ± SD, n.mi.) | Flight variation (mean ± SD, n.mi.) |
|---|---|---|---|
| FMS | 36 | 0.12 ± 0.16 | 0.18 ± 0.10 |
| Conventional | 38 | 0.78 ± 0.55 | 0.76 ± 0.30 |
| Turboprop | 15 | 0.80 ± 0.40 | 0.62 ± 0.27 |

Table 2. Cross-track error, on route (continued).

| Aircraft type | Flight Length (mean ± SD, n.mi.) | Maximum (n.mi.) | Flight Maximum (mean ± SD, n.mi.) |
|---|---|---|---|
| FMS | 91.6 ± 15.7 | 1.45 | 0.59 ± 0.31 |
| Conventional | 97.8 ± 15.3 | 4.60 | 2.34 ± 0.84 |
| Turboprop | 58.3 ± 13.1 | 3.28 | 1.86 ± 0.64 |

After noting the relatively large maximum cross-track errors for the FMS cases, further analysis revealed several anomalies in the radar track data. These anomalies included a systematic error and discrete spikes in the track-position data (i.e., individual track outliers). In addition, several runs were affected by a temporary limitation in the CTAS system.

The systematic error was due to a mismatch between the local coordinate frame used by the CTAS field test system and the one used by the FAA Host system. This mismatch warped the predicted path and resulted in a 1-2 n.mi. position error at many waypoints. Such an error would not be introduced into a field system supported by operational quality-assurance checks. Of the 89 runs presented in tables 1 and 2, 4 FMS-equipped jet flights, 8 conventional-equipped jet flights, and 4 turboprop flights were affected by this system error.

The remaining 73 runs were then inspected for significant radar-track anomalies (cross-track outliers) that appear as a large instantaneous spike in lateral error. Cross-track error "spikes" on the order of one n.mi., found in three runs, were removed from the track data for those runs. Although these anomalies are a reality of current field operations, it is informative to examine cross-track errors without these transient errors. Removal of these errors improves the representation of the actual route-tracking errors and provides a estimate of the performance that could be obtained via "out-board" filtering of the Host data.

Examination of the data also revealed that many of the FMS-equipped jets, on direct paths to the meter fix, experienced their maximum cross-track error near the end of their trajectory. The CTAS system normally models en-route turns with a "fly-by" geometry unless the navigational database designates the fix as a "fly-over" type. However, for turns at the TRACON boundary (meter fix) CTAS modeled the turn as an instantaneous change in course even though aircraft would normally execute a fly-by turn. The impact of this modeling error is a consistent and rapid increase in cross-track error (up to a mile, depending on speed and geometry) as the flight turns into the TRACON. This modeling error, which can be corrected in later versions of CTAS, affected all of the remaining (22) FMS runs.

Tables 3 and 4 present the cross-track error data with all three anomalous conditions removed from the data set. The runs affected by the systematic data were removed completely, while only individual track hits (affected by the other two anomalies) were removed. Results indicate a small reduction in most of the metrics measured. The maximum error for the FMS and turboprop cases was reduced by 0.66 and 0.71 n.mi., respectively. The mean and standard deviation of each flight's maximum error was also reduced for the FMS and turboprop cases by approximately 0.1–0.2 n.mi.

Inspection of the remaining cross-track data revealed a fair amount of noise relative to the remaining error. After applying a binomial-smoothing filter to the cross-track error for each run, the maximum cross-track error for the FMS-equipped jets reduced slightly to 0.65 n.mi. The average of the maximum cross-track error in each flight dropped slightly to 0.27 n.mi. with almost no change in standard deviation. These results are much more consistent with the actual cross-track errors observed in the flight test.[18]

Table 3. Cross-track error, on route, anomalies removed.

| Aircraft type | Runs | Flight average (mean ± SD, n.mi.) | Flight variation (mean ± SD, n.mi.) |
|---|---|---|---|
| FMS | 32 | 0.08 ± 0.09 | 0.13 ± 0.05 |
| Conventional | 30 | 0.72 ± 0.57 | 0.78 ± 0.31 |
| Turboprop | 11 | 0.69 ± 0.38 | 0.58 ± 0.24 |

Table 4. Cross-track error, on-route, anomalies removed (continued).

| Aircraft type | Flight Length (mean ± SD, n.mi.) | Maximum (n.mi.) | Flight Maximum (mean ± SD, n.mi.) |
|---|---|---|---|
| FMS | 93.9 ± 15.0 | 0.79 | 0.37 ± 0.13 |
| Conventional | 98.0 ± 15.2 | 4.60 | 2.30 ± 0.84 |
| Turboprop | 59.7 ± 12.6 | 2.57 | 1.69 ± 0.54 |

It was observed that much of the remaining maximum cross-track error for the FMS cases was caused, not by modeling or pilot-conformance errors, but by initial conditions containing radar anomalies in lateral position or course (relative to the true aircraft position and direction). A lateral error in the initial condition will cause the predicted path to be offset from truth. For on-route flights with this error, the trajectory-generation algorithm models a turn to immediately rejoin the planned route (a similar approach is applied to the initial course). As a result of this approach, the actual cross-track error will initially jump (for the case of an initial-position anomaly) and then decrease towards zero as the flight and predicted course converge. A quantitative analysis of this "initial condition" anomaly is beyond the scope of this paper.

Cross Track Error – Off-route Descents

Descent-profile results for off-route cases were not included in reference 1 because of some unique analysis complexities. These cases involved conventional-equipped aircraft navigating directly to the meter fix without following a STAR. The added complexity arose from a combination of navigational errors and route geometry near the TRACON boundary. These complexities affect both the horizontal and time profiles for the off-route descents. This part will identify these complexities, outline the analysis approach, and present results in terms of the horizontal profile. Related time-profile results are presented in the later off-route part of the Time Profiles sub-section.

The Denver meter fixes are not collocated with a navigational aid, but are defined as a distance along an inbound radial to a navigational aid within the TRACON (Figure 3). Typically, conventional-equipped aircraft require radar vectors to fly direct to a fix defined in this manner. One exceptional case involves a flight coincidentally positioned between the fix and a navigational aid thus allowing the flight to navigate along a radial to the fix. Even then, the distances and signal quality may introduce errors navigational errors greater than that expected for standard routes.

The impact of the off-route navigational errors on trajectory-prediction accuracy was further complicated by the geometry of the direct path and the inbound course into the TRACON. Figure 3 illustrates this complication in terms of the two typical scenarios that were observed during the test.

In the first scenario, navigational errors cause the flight to deviate "north" of the predicted path. The actual path follows this northerly trajectory until the flight intersects the inbound radial and turns towards the TRACON. In the second scenario, navigational errors cause the flight to deviate "south" of the predicted path. The actual path penetrates the TRACON prior to crossing "abeam" the metering fix (with respect to the predicted path). In both scenarios, the cross-track error growth is sensitive to the angle between the en-route path and the inbound radial. In addition, the southerly scenario is further complicated by the interaction with the TRACON. Following the hand off (typically 5-10 n.mi. prior to the boundary), the TRACON controller may vector the flight for sequencing. These vectors may change the cross-track error growth from that which is representative of the original en-route path.

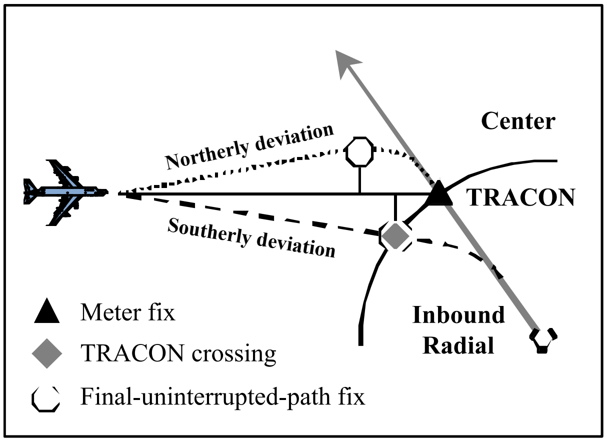


Figure 3. Conventional-aircraft deviations (off route).

Although these complications are an operational characteristic of arrival traffic, they do create a challenge when trying to generalize the data to model typical en-route-vector behavior. For example, in the northerly scenario, the turn onto the inbound radial quickly reduces the cross-track error that would have otherwise continued unabated. For the southerly scenario, TRACON vectors may either increase/decrease the error beyond that associated with the original en-route path.

For the purposes of this paper, a key position is defined as the "final-uninterrupted-path fix." This fix, illustrated in figure 3, separates the en-route portion of the actual trajectory from that which is influenced by the arrival/TRACON geometry. Truncation of the track data, at the final-uninterrupted-path fix, allows the arrival-data results to be used to represent the more general en-route case. This approach will be applied to the cross-track error analysis (here) and again as part of the Time Profile sub-section (for off-route descents). In order to capture the characteristics of arrival predictions, an alternative analysis approach will be incorporated for both the Time- and Altitude-Profile sub-sections. The Time Profile sub-section will also include analysis of the time error at the TRACON boundary. For the analysis of the altitude-profile errors, the actual and predicted trajectories will be compared for the entire predicted path. This approach facilitates comparison of the off-route descent results with those published previously for on-route descents.

During the field test, 38 conventional-equipped aircraft (26 jets and 12 turboprops) were given descent clearances while navigating off route. The analysis excluded 13 cases (10 jets and 3 turboprops). The reasons for exclusion included: deviations for turbulence [2]; deviations for weather [2]; clearance confusion [5]; STAR change for traffic load [1]; late TOD clearance [1]; expedited descent for traffic [1]; and a prediction horizon that was too small (less than 7 min.) [1].

Controllers were requested to handle the off-route navigation with normal operational technique. The controllers applied two techniques: radar vectors, and when feasible, the use of a radial from an en-route navigational aid. Of the 16 off-route jet cases, 6 were confirmed as using radials, 8 were confirmed as vectors, and the remaining 2 were likely to have been vectors. When using vectors, the controllers were often observed to have refined the headings, mid-flight, based on their radar observations. Neither method (radial or vector) exhibited a distinct advantage in terms of minimizing cross-track error. Given the small number of runs, all 16 are combined as one group.

Tables 5 and 6 present the cross-track error data for conventional-equipped aircraft (jets and turboprops). The table compares the results for the on-route cases with that of the comparable off-route cases.

Table 5. Cross-track error, conventional aircraft.

| Aircraft type | Route | Runs | Flight average (mean ± SD, n.mi.) | Flight variation (mean ± SD, n.mi.) |
|---|---|---|---|---|
| Conventional | On | 30 | 0.72 ± 0.57 | 0.78 ± 0.31 |
| Conventional | Off | 16 | 0.81 ± 0.61 | 0.61 ± 0.35 |
| Turboprop | On | 11 | 0.69 ± 0.38 | 0.58 ± 0.24 |
| Turboprop | Off | 9 | 1.70 ± 1.01 | 1.05 ± 0.55 |

Table 6. Cross-track error, conventional aircraft.

| Aircraft type | Route | Flight Length (mean ± SD, n.mi.) | Max. (n.mi.) | Flight Max. (mean ± SD, n.mi.) |
|---|---|---|---|---|
| Conventional | On | 98.0 ± 15.2 | 4.60 | 2.30 ± 0.84 |
| Conventional | Off | 89.7 ± 14.7 | 3.11 | 1.75 ± 0.99 |
| Turboprop | On | 59.7 ± 12.6 | 2.57 | 1.69 ± 0.54 |
| Turboprop | Off | 63.6 ± 8.0 | 6.65 | 3.56 ± 1.92 |

For conventional jets, the mean of the flight-average cross-track errors rose slightly from 0.72 n.mi., to 0.81 n.mi., while the mean of the variation dropped from 0.78 n.mi., to 0.61 n.mi. The standard deviations of both the flight average and variation remained about the same. The maximum cross-track error showed a substantial reduction for the jets whereas the metric rose sharply for turboprops. These results, which are consistent with the observed differences in error-growth for the on-route and off-route cases, are discussed next.

For the on-route cases, cross-track was generally small except for portions of the path near a turn. Depending on the size of the turn, pilot overshoots would lead to increased cross-track error near the turn with even larger variations across flights executing the same turn.[24] This type of cross-track error pattern tends to have small flight-average errors with larger variations. For off-route cases, cross track generally grew over time as the flight proceeded along a poor vector or course. Since the off-route cases do not encounter any significant turns (as in the on-route cases), and large course errors were corrected by controllers, the maximum errors tended to be smaller than that for the on-route cases. The flight variations were also lower because the off-route flights tended to hold heading whereas the on-route flights varied headings to correct course errors (effectively zig-zagging along a route). However, the cumulative impact of the vector errors lead to flight-average errors that were greater than that for the on-route cases.

For the turboprop cases, all of the error metrics increased substantially for the off-route cases. The mean and standard deviation of the flight-average cross-track errors nearly doubled with the mean increasing from 0.69 n.mi. to 1.38 n.mi. The flight variation also nearly doubled (in both mean and standard deviation across all flights). The maximum error metrics also increased by over 100%.

Altitude Profile

This sub-section will present results in three parts. Results for the Off-route Descent advisories will be presented first. A complete analysis of the altitude-profile errors and TOD/BOD-position errors is included, and the results compared to the previously published on-route cases. The second part on Cruise-Altitude Change presents the flight-path-angle errors associated with cruise-altitude-change predictions. The last part, DA Descent Prediction Error, focuses on the previously published on-route descent cases and determines the impact of actual weight-estimation errors on TOD/BOD-position accuracy.

Altitude-Profile Errors – Off-route Descents

Results for the 25 off-route descent cases are presented here and compared to the on-route results from reference 24. The results are based on the difference between the actual and predicted paths over the entire descent. The truncation approach (based on the last uninterrupted-path fix) is not applied here. The analysis for some runs, involving southerly-deviations, will include some errors due to TRACON vectoring. Since the vectors occur close to the TRACON, their influence is local and expected to be small. In any case, the results presented here are of a conservative nature because the TRACON vectors tend to increase altitude-profile error (by increasing the length of descent).

Figures 4 and 5 illustrate the altitude-profile errors for off-route descents flown by conventional-equipped jets and turboprops, respectively.

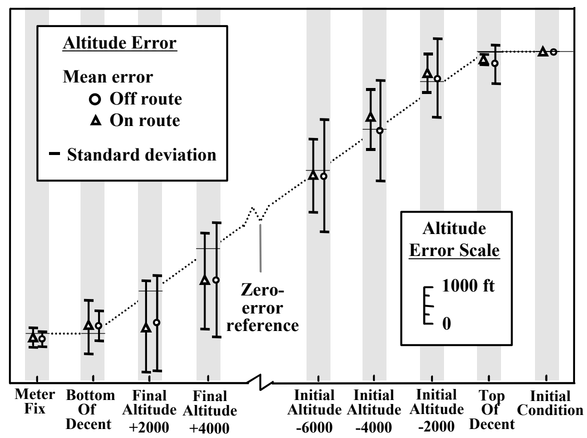


Figure 4. Altitude-profile error, conventional jets.

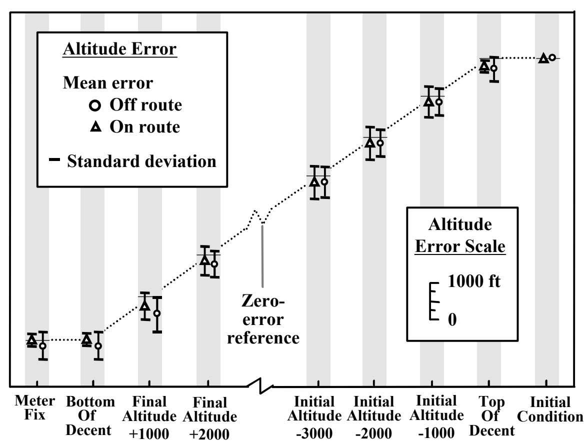


Figure 5. Altitude-profile error, turboprops.

Profiles for the on-route cases (previously published) are also presented for comparison. The figures present the altitude error at common-trajectory events that are defined along the predicted path. Descent events are defined relative to height-below-TOD and height-above-BOD. This approach facilitates comparisons across multiple flights that did not descend between the same altitudes.

Overall, the results indicate similar error profiles for both on-route and off-route cases (for both types). Closer examination of the jet cases reveals that the variation in error is substantially larger at nearly every altitude event (up to approximately 400 ft. larger). Aside from the mean error being low at the TOD (approximately 300 ft), the off-route jet cases exhibit the same sort of shape as the on-route cases. That shape is characterized by the mean error starting above predicted at the higher altitudes followed by the mean falling below path mid-way through the descent. Another shared characteristic is the growth in variation along the descent.

In both cases (on-route and off-route), flights tended to fall below path. This suggests an error in the modeling of atmosphere and aircraft performance, and/or navigational errors which effectively cause the flight to traverse a greater distance over the descent. Although the on-route cases were affected by an error in the distance flown (reference 24), distance was not a primary factor for the off-route cases. Additional discussion regarding performance modeling is presented in the following part on DA Descent-Prediction Error.

The turboprop cases exhibit even fewer differences between on-route and off-route cases. Compared to the jets, turboprops experienced substantially smaller errors. That result is not surprising given the nature of turboprop operations (characterized by more-responsive thrust control, slower speeds, and slower descent rates than that for jets). These factors, combined with the fixed flight-path-angle descent technique (common to propeller-airplane operations) contribute to greater descent-altitude-profile predictability.

Following the convention of earlier CTAS field-test reports, results for the same altitude profiles are presented next in terms of the along-track TOD/BOD position errors. For the purposes of this analysis, BOD-position errors were computed based on the position corresponding to 1000 ft above the BOD altitude. This approach improved the accuracy of the measurement by avoiding most of the variation in pilot level-off technique. The results for TOD and BOD accuracy are presented in tables 7 and 8, respectively.

It is interesting to note the increase in TOD-position error (mean and variation) when the off-route cases are compared to the on-route cases. Jets tended to initiate their TOD up to 0.92 n.mi. earlier for off-route vs. on-route cases. This is consistent with the below-path errors in the altitude-profile plots. It is likely that this larger error is due to the navigational challenges associated with the off-route cases. Most of the flights navigated by radar vectors and were not directly aligned with a navigational aid. When a pilot attempts to determine a specific TOD position via distance measured from a fix, the accuracy of that position is sensitive to alignment. Depending on alignment, cross-track error also contributes to along-track TOD error. Turboprops exhibited a similar TOD behavior with a slightly smaller difference between on-route and off-route cases.

Table 7. TOD errors, conventional aircraft.

| Aircraft type | Route | Runs | TOD error (mean±SD, n.mi.) | TOD Min/Max (n.mi.) |
|---|---|---|---|---|
| Conventional | On | 38 | -0.39 ± 1.39 | -4.2/2.7 |
| Conventional | Off | 15 | -1.31 ± 2.74 | -7.7/3.0 |
| Turboprop | On | 15 | -0.80 ± 1.18 | -2.7/1.1 |
| Turboprop | Off | 9 | -1.16 ± 1.37 | -2.8/1.8 |

(+/- indicates late/early)

Table 8. BOD errors, conventional aircraft.

| Aircraft type | Route | Runs | BOD error (mean ± SD, n.mi.) | BOD Min/Max (n.mi.) |
|---|---|---|---|---|
| Conventional | On | 38 | -3.87 ± 4.17 | -11.2/11.3 |
| Conventional | Off | 15 | -3.68 ± 4.31 | -11.0/3.0 |
| Turboprop | On | 15 | -0.84 ± 1.54 | -4.1/1.6 |
| Turboprop | Off | 9 | -1.12 ± 1.85 | -4.1/2.4 |

(+/- indicates late/early)

Regarding BOD error, results for the conventional jets were a surprise. It was expected that off-route descents would have greater BOD error than on-route descents. Although this held true for the turboprop cases, the difference was small. Furthermore, the jets exhibited a slight improvement in mean BOD error. With regard to the range in error (maximum to minimum) the off-route cases appear to have a much greater difference. However, it is likely that the large overshoot case (11.3 n.mi.) was an outlier. The remaining cases were much tighter with the next largest overshoot being only 2.4 n.mi. If the large overshoot case is ignored, there would be very little difference in the BOD metrics for jets between on-route and off-route cases. It was not clear what factors lead to these results, but the data does suggest the usefulness of lateral (if not vertical) navigational aids in the cockpit.

Cruise Altitude Change

During the field test, cruise-altitude-change clearances were issued to 23 flights. One case is excluded from the analysis because of a descent interruption outside the scope of the test. Of the 22 remaining flights, 7 were conventional-equipped jets, 9 FMS-equipped jets, and 6 turboprops. 18 of the runs were given instructions to hold their current indicated airspeed during the altitude change (performing a typical delay absorption maneuver) while the other 4 were not given specific speed instructions (performing a typical conflict resolution maneuver). At least two of the flights were requested to expedite their descents, for traffic unrelated to the test.

The goal of this part of the test was to gather data to validate the flight-path-angle model and determine an appropriate value. Table 9 presents the mean and standard deviation of each flight's average flight-path angle. The average angle was calculated by a linear "best fit" to the actual altitude data. The two "expedited" flights are presented separately from the table.

Table 9. Flight-path-angle data.

| Aircraft type | Runs | Average flight path angle (mean ± SD, degrees) | Min. (degrees) | Max. (degrees) |
|---|---|---|---|---|
| All | 20 | -1.6 ± 0.6 | -0.8 | -2.9 |
| Jets | 14 | -1.5 ± 0.6 | -0.8 | -2.9 |
| Conventional | 6 | -1.2 ± 0.4 | -0.8 | -2.1 |
| FMS | 8 | -1.7 ± 0.6 | -1.1 | -2.9 |
| Turboprops | 6 | -1.7 ± 0.5 | -1.1 | -2.5 |

The results in table 9 indicate that average flight-path angles differed significantly from the 3-degree value assumed for the test. The actual descents were, on average, half as shallow as the predicted trajectories. The conventional-jet category was found to have the shallowest descent while the FMS-jets and turboprops were slightly steeper and appear relatively similar. Although there is no obvious reason why the avionics equipage should affect the jet results, it is likely that the differences between the two jet categories is due to the performance/operating differences of the individual types within those categories.

The two expedite cases were separated from the table to be consistent with the DA-design philosophy, namely to differentiate separate cases of intent (e.g., expedites vs. nominal) via unique controller-intent inputs. In any case, the results for all cases are presented. One was a conventional jet with a best-fit flight-path angle of –2.54 degrees (the steepest descent of the conventional-jet cases). The other expedited case was an FMS-equipped jet with a best-fit flight-path angle of –2.1 degrees. Though this was on the steep end of the FMS-cases, there were two other cases with close to the same flight-path angle. Since expedite instructions could not be confirmed for those cases, they are included in table 9 for completeness.

A significant factor that differentiates these en-route cruise-altitude changes from the arrival descents is the pilot's thrust-management technique. For arrivals, jet-users prefer to descent at near-idle thrust (resulting in descent angles of approximately 3.1 degrees). However, for en-route altitude changes, users often prefer to prolong a required descent for economic reasons. The only legal requirement is for the pilot to maintain a descent rate of at least 500 ft/min (unless otherwise instructed by ATC, e.g., expedite).[32]

It is also interesting to note that the variation in the average flight-path angle was generally in the range of 30-38% of the mean. Assuming a mean of 1.6 degrees (approximately equivalent to descent ratio of 6 n.mi. per 1000 ft), a 38% error in flight path angle would result in an altitude-error growth of approximately 100 ft. per n.mi. of descent. Altitude errors, which tend to accumulate over the descent, will lead to a ground-speed error (due to errors in the TAS and wind-on-path profile predictions). Based on a standard atmosphere, a typical jet descent at 300 KIAS in the vicinity of FL250 would result in a TAS error on the order 6.5 knots (3.6 knots) for each 1000 ft. of altitude error. Turboprops, typically descending at 160 KIAS in the vicinity of FL200, would result in a TAS error on the order 3.6 knots for each 1000 ft of altitude error. For a cruise-altitude change of 40 flight levels (approximately 4000 ft), the altitude error would result in an average TAS error of 4.8 knots for the typical jet (2.7 knots for the typical turboprop). The resulting time error at the predicted "end-of-descent" position would be approximately 2 sec for the typical jet (5 sec for the typical turboprop).

DA Descent-Prediction Error

This part revisits the on-route descent cases, published previously, to determine the impact of weight estimation error on the altitude-profile. Reference 23 presented results for 89 on-route descent cases (15 turboprops and 74 jets). Since the turboprop descent procedures are relatively insensitive to weight, only the jet cases are investigated.

A total of 35 flights down-linked their descent weight to CTAS. The CTAS default-weight estimates, and the actual weights for the 35 cases, are presented in table 10. The CTAS weight-estimation errors ranged between 4.6-7.2% in mean with standard deviations ranging from 2.6-6.3%. Although corrections to the CTAS default-weight estimates could reduce the mean error, a reduction in the variation requires additional per-flight data that could be obtained via an expanded flight plan or air-ground data link.

Table 10. Descent weights, estimated and actual.

| Aircraft type | Runs | CTAS weight estimate (/1000 lb.) | Weight error (mean ± SD, /1000 lb.) |
|---|---|---|---|
| B737 | 7 | 98.0 | -6.4 ± 5.8 |
| B727 | 4 | 140.0 | 6.8 ± 4.4 |
| DC10 | 5 | 344.5 | -23.0 ± 14.0 |
| B757 | 4 | 174.2 | 11.6 ± 4.8 |
| B73S | 15 | 100.0 | 7.2 ± 5.5 |

Since the down linked weight data influenced CTAS predictions, the TOD/BOD results in reference 24 contain a mix of cases with and without weight error. For consistency, the 35 actual-weight cases were adjusted, via simulation, to reflect the accuracy that would have resulted from the CTAS default weight. Although the results indicated little change in the metrics for the conventional-jet descents, the FMS TOD predictions improved by 0.38 n.mi. (15%) in mean.

Since the FMS-DA procedure provides for an uninterrupted descent along the FMS vertical path, the FMS TOD error is a direct measure of both the precision between the FMS and CTAS predictions, and the accuracy of the CTAS prediction. The BOD is not as interesting since both CTAS and the FMS do a good job of targeting the BOD. Although CTAS computes TOD in a manner similar to a performance-based FMS, differences may exist in terms of performance and atmospheric modeling. For conventional jets, the BOD is of interest because it indicates how well the CTAS TOD-advisory performed. The goal is to deliver the aircraft to the meter-fix at just the right altitude and speed without excess flight at the lower altitudes. By comparison, the TOD analysis represents the accuracy with which the pilots executed the DA-based clearance.

A more enlightening comparison would be to focus on only the runs for which the weight data was known. Table 11 presents the TOD/BOD errors based on corrections for the actual vs. CTAS-default weights. The results indicate that the use of correct weight data would have lead to a 1.3 n.mi. improvement in the mean CTAS-TOD prediction for FMS jets, and 0.7 n.mi. improvement in the CTAS-BOD prediction for conventional jets.

Table 11. TOD/BOD error vs. weight.

| Aircraft type | TOD error (mean ± SD, n.mi.) | | BOD error (mean ± SD, n.mi.) | |
|---|---|---|---|---|
| Weight ref.:. | CTAS | Actual | CTAS | Actual |
| FMS | -3.4 ± 2.2 | -2.1 ± 2.6 | -0.1 ± 0.8 | 0.05 ± 0.9 |
| Conventional | -1.0 ± 1.6 | -1.0 ± 1.6 | -5.2 ± 3.5 | -4.5 ± 3.3 |

Other measurable factors that influenced the BOD accuracy for the conventional-jet descents included the TOD error, distance flown, and performance-model bias. For the cases studied in this test, the actual TOD errors accounted for 0.96 n.mi. of the mean BOD error, while the excess distance flown (due to conventional-navigation errors in cross track and turn overshoots) accounted for an additional 0.22 n.mi. of the mean BOD error. The BOD error, when adjusted for both the TOD and distance-flown errors, was computed to have a mean of 3.28 n.mi. early with a standard deviation of 3.66 n.mi.. These results are approximately 50% higher than the comparable FMS-TOD errors which are not subject to significant errors in TOD and distance flown. Much of the remaining difference may be attributed to identifiable errors in the CTAS performance modeling. Based on the results of earlier field tests (reference 21) a 5% bias was introduced to the CTAS conventional-jet models to force the DA-advised TODs to be approximately 5% earlier. The bias was not added to correct the model, but actually degrade it based on feedback from conventional-jet pilots who wanted to err on the low side of descents. This bias, which added approximately 2 n.mi. to each descent, accounts for the remaining differences between the conventional-BOD and FMS-TOD results.

Time Profiles

Cruise Speed

The cruise-speed adjustment is an effective method for time control (for both en-route and arrival metering), and can provide a small level of flexibility in conflict resolution. This maneuver can be particularly useful (to both controllers and users) given that controllers are supported by CTAS-performance models which provide the controller with advisories based on custom-data for each type. This modeling approach enables the system to translate complex performance envelopes into simple advisories that enable the controller to take advantage of the unique characteristics of each aircraft type. When combined with descent planning, cruise-speed selection is a critical parameter for fuel-efficient time-constrained trajectory planning. For typical arrival-metering conditions the cruise-speed maneuver is useful for delays ranging from 1-4 min depending on aircraft type and speed.

For this test, 28 participating flights received cruise-speed adjustments ranging from 10-30 KIAS. The results here are based on 22 of the runs: 6 runs were dropped for experimental reasons. The adjustments were split between accelerations and decelerations with an attempt to obtain an even distribution across the participating aircraft types. The cruise portion of the trajectories were studied up to a reference position (10 n.mi. prior to TOD), and typically ranged in distance from 40-110 n.mi.. The limitation in cruise-segment length was due to a FAA constraint, at the time of the test, limiting track data to arrivals only.

Three dimensionless quantities, Normalized Time-Error, Speed Control and Control-Time Error, were derived from the raw trajectory data to validate and quantify the test results. Normalized Time Error, $t_{error}$, is defined as: $[(t_{actual} - t_{predicted}) \times 100] / t_{actual}$ which indicates the time error percentage of the total time to fly to the reference position. Speed Control, $v_{control}$, is defined as: $(v_{ground\_original} - v_{ground\_final}) / (v_{cas\_original} - v_{cas\_final})$ which indicates the ground-speed per unit IAS change. Control-Time Error, $t_{control\_error}$, is defined as: $(t_{actual} - t_{predicted}) / (t_{original} - t_{final})$ where $t_{original}$ is the time to fly to the reference position if there is no speed change. It is the ratio of the time error to the delay (desired time change) that needs to be absorbed.

The data set were checked for validation in cruise speed analysis. Data were removed if the cruise speed change clearance was not clearly understood by controllers and pilots. Final statistical analysis was applied to 89 jets. Among these jets, 22 have cruise speed change and 67 have no cruise speed change. Only 4 turboprops have valid test results for this analysis therefore no statistical analysis was done for turboprops.

Table 12 presents the Normalized Time Error ($t_{error}$) as a function of aircraft type and acceleration case. A typical error of 2% translates directly into an along-track time error of 24 sec for a 20 minute trajectory prediction (or approximately 3 n.mi. for a jet at 450 knots). The overall mean error was approximately 1% early with variation of 2.36%. There was little difference in the results for the FMS types (all), compared to the conventional types (all), which is consistent with the expectation that the avionics differences would not introduce significant differences in holding airspeed.

As shown in table 12, the average $v_{control}$ of the jets that were sped up is greater than the jets that were slowed down. This difference is primarily related to the difference in initial cruise speeds between acceleration/deceleration cases. The accelerated flights, on average, started their runs at speeds that were slower than that for the decelerated cases.

Table 12. Cruise-speed time error.

| Aircraft type | Runs | $t_{error}$% mean±SD | $v_{control}$ mean±SD | $t_{control\_error}$ mean±SD |
|---|---|---|---|---|
| FMS (fast) | 4 | 1.17±2.26 | 1.70±0.36 | -0.17±0.43 |
| FMS (slow) | 5 | -1.84±1.53 | 1.51±0.1 | -0.40±0.39 |
| FMS (all) | 9 | -0.5±2.37 | 1.60±0.25 | -0.15±0.48 |
| Conventional (fast) | 5 | 1.63±2.84 | 1.62±0.18 | -0.38±0.58 |
| Conventional (slow) | 8 | -0.89±1.41 | 1.51±0.1 | -0.15±0.32 |
| Conventional (all) | 13 | 0.08±2.34 | 1.55±0.14 | 0.05±0.49 |
| All jets (fast) | 9 | 1.43±2.45 | 1.66±0.26 | -0.29±0.50 |
| All jets (slow) | 13 | -1.26±1.48 | 1.67±1.39 | -0.24±0.36 |
| All jets (all) | 22 | -0.16±2.31 | 1.57±0.19 | -0.03±0.49 |
| All jets (no change) | 67 | -1.06±2.36 | NA | NA |

Table 12 also presents the Control-Time Error ($t_{control\_error}$,), the inverse of which is analogous to a "signal-to-noise" ratio for speed control. For all jets, all speed changes, the Control-Time Error had a mean value of 3% delay with a variation of 49%. The mean speed changes issued for jets were approximately 19 KIAS with a standard deviation of 10 KIAS. Most of the prediction error may be attributed to the uncertainty in each flight's initial TAS, and the pilot's ability to track the new speed clearance, which is relatively insensitive to the new speed selected. It may be reasonable to expect that $t_{control\_error}$, would reduce for speed changes larger than those evaluated in this test. For those cases evaluated in the test, the mean error was approximately 3% of the desired delay control.

Another interesting result stems from the comparison of $t_{error}$ for cases with speed change and cases without speed change. The latter set represents the classic factor affecting en-route conflict-probe, namely the uncertainty in estimating a flight's current speed. The variation in $t_{error}$ for cases with cruise-speed change (all jets) is very close to the variation for cases without cruise-speed change. This indicates that the trajectory predictions are just as accurate for flights with cruise-speed changes as they are for flights without. This is consistent with the observation that the primary error source for cases without speed change, the radar tracker, introduces a similar amount of speed uncertainty as does the primary error source for cases with speed change, the wind predictions. Field test results indicate that the en-route radar-tracker-velocity estimates, for steady-state cruise, are approximately 12 knots.[18] Studies of the current en-route wind prediction system (the Rapid Update Cycle) indicate an RMS velocity error on the order of 10-12 knots at cruise altitudes.[27,33] These errors are on par with the 2.3% standard deviation observed for $t_{error}$ in both cases.

Pathstretch Advisory

The primary error source for this maneuver is the precision with which the controller and pilot execute the maneuver. Other factors include errors in wind prediction and the estimated velocity. Depending on the navigational geometry involved, the wind errors may not introduce any more error than that which would be expected for other routing options. The primary error source introduces uncertainty in the actual completion of the turn back. In addition, the larger the angle of the turn back, the greater the sensitivity of the maneuver to errors in executing/modeling the turn. For a 90 degree turn back, each mile of overshoot translates into approximately one mile of added path flown (equivalent to approximately 8 seconds error in predicted along-track position. Of the ten cases studied in this test, the turn-back angles varied between 50–81degrees with a mean and standard deviation of 61 and 10 degrees, respectively.

The pathstretch time-error was calculated with respect to the pathstretch reference fix, illustrated in figure 6, which corresponds to the end of the turn back. The time error is determined by comparing the predicted time at the reference fix to the time associated with the actual radar track when the flight passed abeam the reference fix. For the purpose of this analysis, the remainder of the trajectory is ignored here because it is analyzed as part of the descent cases presented in reference 24 and other parts of this paper. The results are presented in table 13.

Although only a small number of runs were obtained due to the operational limitations of the field test, these cases provide some insight into the accuracy that can be achieved with this type of maneuver. In general, the time errors are on par with those for the descent-speed advisories, and are on par with the accuracy associated with a 10–15 minute cruise-speed-advisory prediction. In addition, the data does not suggest a significant difference based on avionics equipage, a result that would be expected given that the maneuver is essentially a timed change in heading.

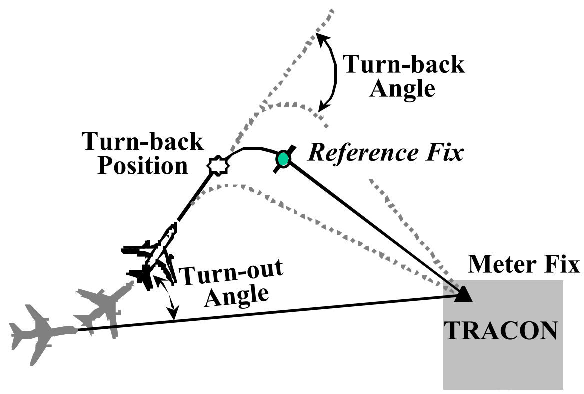


Figure 6. Pathstretch illustration.

Table 13. Pathstretch time error after turn back.

| Aircraft Type | Runs | Time error after turn (mean ± SD, sec) | Min. (sec) | Max. (sec) |
|---|---|---|---|---|
| All | 10 | 2.6 ± 15.6 | -20.2 | 26.3 |
| Conventional | 5 | 5.4 ± 15.2 | -10.5 | 25.9 |
| FMS | 5 | -0.2 ± 17.2 | -20.2 | 26.3 |

Time Profile – Off-route Descents

This part completes the trajectory-prediction accuracy analysis for the 25 off-route descent cases. As mentioned in the earlier sub-section on cross-track error analysis, the off-route descent cases were influenced by an error associated with off-route navigation near the TRACON. For the purposes of this part, the time errors are presented with respect to two reference positions. The first set of results presented is based on the final uninterrupted-path fix. These data are independent of the arrival/TRACON geometry and are applicable as an en-route conflict probe metric. The second set of results is based on the actual TRACON entry. These data are applicable as a metering metric and do not apply as a conflict-probe metric. It is worth noting that the meter-fix time-error results for the on-route descent cases are comparable to the all of the results in this sub-section. The meter-fix reference is on the TRACON boundary and the arrival paths were not deviated in course near the TRACON.

Table 14 summarizes the time-error results, for both on-route and off-route descents, based on the final uninterrupted-path fix.

Table 14. Time error at the last uninterrupted-path fix .

| Aircraft type | Route | Runs | Time error (mean ± SD, sec) | Time error (Max, sec) |
|---|---|---|---|---|
| Conventional | On | 38 | 5.5 ± 15.2 | 29.6 |
| Conventional | Off | 16 | -0.6 ± 14.0 | 20.1 |
| Turboprop | On | 15 | -1.6 ± 15.4 | 31.1 |
| Turboprop | Off | 9 | 3.4 ± 19.4 | 34.4 |

(+/- indicates late/early)

The results indicate that the mean time error was 4.7 sec earlier for off-route jets (Conventional), than that for on-route jets, with only a slight difference in deviation. This result is interesting because the altitude-profile errors indicated a substantially larger variation for the off-route cases. A larger altitude-error variation would contribute to larger variations in ground speed and time. However, one contributing factor was due to the navigational errors (turn overshoots) associated with the on-route cases. Adjustments to the on-route cases (for turn overshoots) reduce the time error to a mean of 2.7 sec (late) with a standard deviation of 13.3 sec. This adjustment accounts for much of the difference in mean time error (on-route vs. off-route) and decreases the on-route variation below that for the off-route cases.

Turboprops differed from jets in that the mean time error was 5 sec later for off-route cases than that for the on-route. In addition, the standard deviation of the time error increased by 4 sec (for off-route cases) and the maximum error was observed to be 3 sec greater. Given that the on-route turboprop cases were also subjected to turn overshoot s (contributing 3.6 sec to the variation in time error), and the fact that the off-route altitude profiles showed little difference from the on-route profiles, it is not clear what factors lead to the differences in time accuracy.

The remainder of the time-error analysis will focus on the TRACON entry time, a metric that is applicable to metering. The following results are based on a comparison of the actual TRACON entry compared to the predicted time at the meter fix.

The TRACON arrival-time metric is sensitive to the geometry of the arrival path, relative to the TRACON boundary, and is therefore dependent on the airspace and flight paths tested. The sensitivity is greatest for an arrival path that is tangential to the TRACON boundary and least for a path that is orthogonal to the boundary. The focus of this analysis is on jets only, the turboprop paths were on paths that were coincidentally close to being orthogonal to the TRACON boundary. This resulted in little difference between the TRACON time error and the results presented in table 14 (i.e., the actual time associated with the meter-fix, TRACON-boundary, and the "last uninterrupted-path fix" were the same).

Table 15 summarizes the time-error results, for off-route descent cases (jets only), based on the TRACON entry. For comparison, the table also includes the time-error results for the on-route descent cases published previously.

Table 15. TRACON boundary time error.

| Aircraft type | Route | Runs | Time error (mean ± SD, sec) | Time error Max, sec |
|---|---|---|---|---|
| Conventional | On | 38 | 5.5 ± 15.2 | 29.6 |
| Conventional | Off | 16 | -10.8 ± 24.0 | -55.1 |

(+/- indicates late/early)

The results indicate that the TRACON time error was dramatically higher for the off-route cases compared to the on-route cases. The mean and maximum error signify that the off-route aircraft crossed the TRACON boundary significantly earlier than predicted (on average, 10.8 seconds early with the worst case being 55 seconds early. The large variation reflects the mixture of "southerly-" and "northerly-" deviation scenarios (8 each) with the southerly cases exhibiting a larger time error per run.

The primary reason for larger errors per run for the southerly cases is the path geometry. The southerly cases enter the TRACON prior to reaching a position which is abeam the meter fix (based on the predicted path). The more tangential the arrival path, the greater this error will be for a certain magnitude of cross-track error. In comparison, the northerly cases tend to track the inbound radial into the TRACON and cross abeam the meter fix. The relatively shallow (tangential) paths observed for the off-route jet cases tended to make the southerly-deviation scenario more sensitive to cross-track error than the northerly-deviation scenario.

## Concluding Remarks

DA field testing has generated a broad set of data for validating en-route trajectory-prediction accuracy. Field-test data was analyzed for a variety of aircraft types and clearance advisories including cruise speed, cruise altitude, pathstretch (delay) vectors, and descent-speed profile with TOD. The goal in obtaining these results was to validate the accuracy of the CTAS en-route advisories and to generate a database for the development of conflict-probe error models based on aircraft type and trajectory segment.

Overall, results indicate that arrival-time accuracy, in terms of the standard deviation of arrival-time error, were consistently on the order of 15-20 seconds (or less) for all advisory types. This error may be reduced, if necessary, through the use of additional corrective advisories or system improvements that reduce errors in wind prediction, aircraft-state information (velocity and weight), and aircraft-performance models. Regarding cruise-speed advisories in particular, predictions based on speed changes were as accurate as predictions based on speed tracking (the primary case for conflict probe).

Cross-track errors for FMS-equipped jets were substantially smaller than that for conventional aircraft, and within the noise of the radar tracker (approximately a quarter of a mile). Cross-track errors for conventional aircraft were also sensitive to the navigation geometry (e.g., turn size) for both on-route and off-route cases. Conventional jets exhibited little difference between on-route and off-route navigation with maximum errors on the order of 2 n.mi. (mean) with a standard deviation of 1 n.mi. Turboprops on the other hand, experienced twice the error when navigating off route (as compared to on route) with maximum mean errors on the order of 3.5 n.mi. with a standard deviation of nearly 2 n.mi.

With regard to altitude-profile predictions, results for off-route descents were remarkably similar to those for the on-route descents. The mean-error profile for conventional jets was very close, generally within 1000 ft of the predicted path. The variation was slightly higher for off-route descents with the maximum variation on the order of 1500 ft. Turboprops exhibited very little difference , at all, in altitude profile. The off-route navigation did reduce the accuracy with which pilots executed the TOD. Conventional jets, which were the most sensitive, exhibited an increase in mean error of approximately 1 n.mi. and a near doubling of the variation to 2.74 n.mi. Turboprops exhibited a slight increase resulting in a combined error (mean + standard deviation) of less than 2.5 n.mi.

With regard to weight estimation for descent predictions, the results indicated a CTAS database error on the order of 4.6-7.2% (depending on aircraft type), with a variation on the order of 2.6-6.3%. The impact of these errors on descent prediction (TOD/BOD location) was small (on the order of one mile) relative to other sources of vertical-profile error.

For cruise-altitude changes, results indicated a mean flight-path angle of 1.6 degrees. However, a higher fidelity model may be required to reduce the variation which was observed to be 0.6 degrees.

Field testing of CTAS-based en route tools will continue with an emphasis on the evaluating actual conflict prediction/resolution problems. It may also be useful to extend CTAS field testing to evaluate ascent trajectory predictions, the phase of flight which is the most dependent on aircraft-performance modeling and weight estimation errors.

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